PROBING DENSITY FLUCTUATIONS USING THE FIRST RADIO SURVEY

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1. Introduction

For decades, the clustering of luminous objects has been used as an indirect probe of the density fluctuations in the universe. Although the relationship between luminous objects and mass in the universe is not fully understood, it has been hoped that the observed evolution of clustering of different luminous populations might constrain many cosmological unknowns – the geometry of the universe, the nature of any non-luminous matter, the nature of density fluctuations in the early universe and hence the physics of the early universe. Indeed, models for structure formation which are based on variants of the 'cold dark matter' (CDM) model have received much attention largely because they have been fairly successful at predicting the clustering of luminous objects.

Much information on the clustering of nearby populations has been obtained from optical and infra-red surveys of galaxies (and of clusters of galaxies). In addition, Peacock and Nicholson (PN, 1991) investigated the clustering of bright ($S_{2.7} > 1$Jy) nearby ($0.01 < z < 0.1$) radio galaxies. The new radio surveys provide an opportunity for investigating the clustering of much fainter radio sources. Probing density fluctuations with a different tracer provides interesting information on the relative 'bias' of different populations and, of course, one might hope that the great depth and large area covered by the new surveys can be used to probe clustering at higher redshift and on larger scales than was previously possible.

2. Measuring the correlation function in the FIRST Survey

The FIRST survey has now been extended to include a total of $3000\,\mathrm{deg}^2$ of sky yielding a catalog of about 250,000 sources with $22° < \delta < 42°$. and $7^h30^m < \alpha < 17^h30^m$. Details of the mapping and catalog generation can be found in Becker et al. (1996) and in White et al. (1997). Details of how the angular correlation function (CF) is measured can be found in Cress et al. (1996). Here, we use the CF estimator given by Landy and Szalay (LS, 1993): $w(\theta) = [DD(\theta) - 2DR(\theta) + RR(\theta)]/RR(\theta)$.

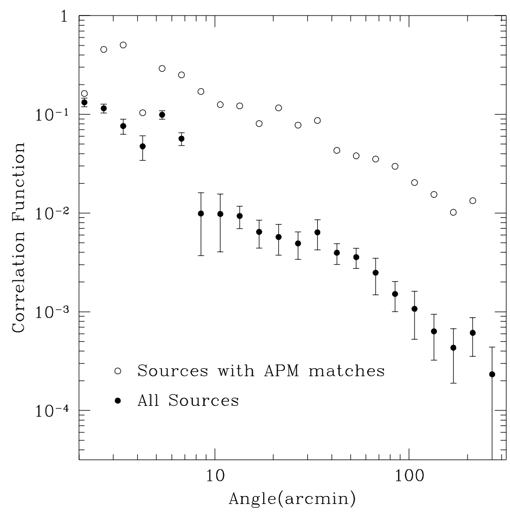

Figure 1. The correlation function for (i) all sources and (ii) for those sources which are identified with E<19 galaxies in the APM survey.

While single objects are sometimes resolved into two or more sources in the catalog, it appears that these extra sources at small separations do not contribute to the correlation function at larger separations (see Cress et al. 1996). Error bars are obtained using the 'partition bootstrap method' in which the CF is calculated for 10 subdivisions of the survey region and the standard deviation of these measurements at each angle is used as a measure of the error. All areas in the survey where the rms noise is less than 0.2 mJy were used in the analysis. CF parameters were determined from a straight line fit to the log-log plots.

We also investigated the CF of FIRST sources in the catalog that have a galaxy with $E < 19$ within $3''$ in the APM catalog of the POSS I survey plates.

Writing the angular CF as $w(\theta) = A\theta^{1-\gamma}$ with θ measured in degrees, we find $A = 0.002$, $\gamma = 2.1$ for the whole sample and $A = 0.04$, $\gamma = 1.8$ for the APM matches.

3. Inferring spatial information

The spatial CF, ξ, is related to the angular CF via Limber's equation.

$$w(\theta) = 2\int_0^\infty \int_0^\infty \left(\frac{dN}{dz}\frac{1}{N}\right)^2 \xi(r,z)dxdu, \tag{1}$$

where the physical separation is given by $r^2 = a^2(t)[u^2/F^2(x) + x^2\theta^2]$, u is the difference in radial distance to two sources, x is the average distance to the two sources, θ is the angle between the sources in radians, a is the scale factor and $F = 1$ in a flat universe (Baugh and Efstathiou, 1993).

If ξ has a power-law form and density perturbations evolve linearly then we can write $\xi(r,z) = (r/r_0)^{\gamma}(1+z)^{-2}$ (in comoving coordinates). We can then estimate $\frac{dN}{dz}$ using luminosity functions give in Dunlop and Peacock (DP, 1991) or Condon (1984). Using the LS estimator of the CF and DP's models 1 to 5 we obtain an r_0 around $8h^{-1}$Mpc. DP's model 7 and Condon's model give slightly lower values: between $8h^{-1}$Mpc and $6h^{-1}$Mpc. (Note that the r_0 derived in Cress et al. uses the CF given by a different estimator – we later found the LS estimator to be more robust to changes in survey geometry). The r_0 results depend on the assumed evolution but the derived clustering appears fairly similar to the clustering of galaxies detected in the optical.

Of course, the spatial CF is not necessarily well-represented by a pure power law and it is interesting to take spatial CF's predicted by CDM models and investigate what they imply for the clustering of objects with the redshift distribution of FIRST sources. CDM makes predictions for how the *mass* clustering evolves but one must also consider the possiblity that the luminous sources are 'biased' (Kaiser 1987) relative to the mass distribution.

In CDM models one starts with a scale-free primordial power spectrum, $P(k) \propto k^n$ (where k is the comoving wavenumber). This $P(k)$ is then 'processed' according a transfer function for CDM. At the epoch at which structure begins to grow $P(k) = P_0\, k^n\, T^2(k)$, where $T(k)$ for CDM is given by Bond & Efstathiou (1984) and P_0 is the normalisation. We normalise to COBE 4-year data using Liddle et al.'s (1996) formula which is valid for spatially flat models.

In the linear regime, the time evolution of the power spectrum can be calculated analytically and depends only on the expansion of the Universe. It is given by $P(k,z) = P(k, z=0) \times G^2(\Omega_0(z), \Omega_\Lambda(z))/(1+z)^2$ where the growth factor, G, is given in Carroll, Press & Turner (1992). Note that $G(\Omega_0 = 1, \Omega_\Lambda = 0) = 1$.

In the highly non-linear regime, the CF obtained from a scale-free primordial spectrum obeys a simple scaling relation (Groth & Peebles 1977). One can interpolate between the linear and highly non-linear regimes to produce semi-analytic models for clustering in the quasi-linear regime which can then be accurately fit to results from N-body simulations (Hamilton 1991; Jain, Mo, & White 1995; Peacock & Dodds 1996). Following the discussion of PD, we define the dimensionless power spectrum as $\Delta^2(k,z) \equiv (2\pi^2)^{-1} k^3 P(k,z)$. The non-linear dimensionless spectrum is then given by $\Delta^2_{NL}(k_{NL}, z) = f_{NL}[\Delta^2(k,z)]$, where the linear and nonlinear scales are related by $k = [1 + \Delta^2_{NL}(k_{NL})]^{-1/3} k_{NL}$. The form of f_{NL} for various values of Ω_0 is given in PD.

Once we have an expression for the power spectrum (including contributions from non-linear evolution) at all epochs, we can Fourier transform this and substitute into Limber's equation to obtain an estimate of the predicted angular CF.

Figure 2(a) shows how the predictions for $w(\theta)$ vary for different estimates of the redshift distribution and how they change when non-linear evolution is considered. There appears to be a fair amount of uncertainty in the predicted result, depending on which $\frac{dN}{dz}$ model is chosen. It should be noted, however, that Condon's luminosity function is more carefully constructed to fit the low-z population and it is these sources that one expects to be contributing most to the clustering signal (see below). In addition, Peacock has indicated that DP's model

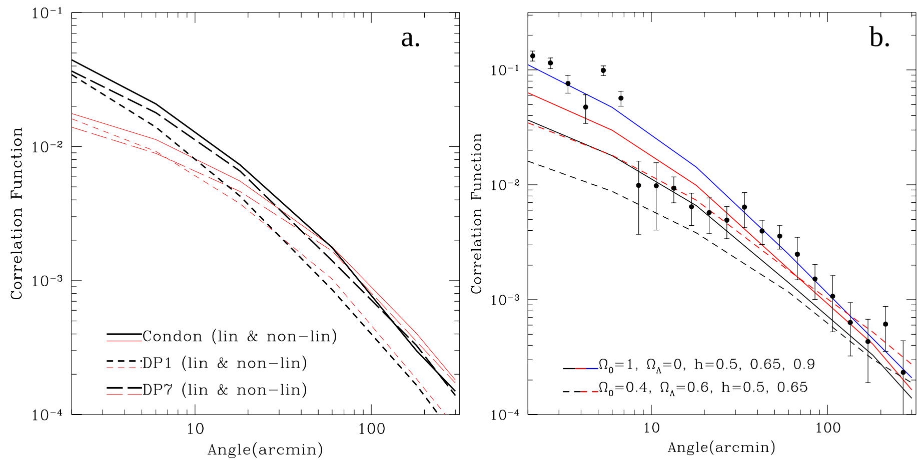

Figure 2. CDM predictions for $w(\theta)$. (a) shows the effect of varying the assumed redshift distribution and the effect of including non-linear evolution in an $\Omega_0 = 1$, $H_0 = 50$ universe (bold curves include non-linear evolution). (b) shows the effect of varying the cosmological parameters using the DP7 redshift model (CF amplitude increases with increasing H_0).

7 is the best model to use. If one limits oneself to only these two models then uncertainties in the redshift distribution do not contribute very significantly to uncertainties in the predicitions. The effect of non-linear evolution is significant on scales less than $\sim 30'$.

4. Discussion

It is useful to investigate how one expects the contribution to the clustering signal to vary with redshift. Since Condon's model and DP7 include a large local population, these two models predict a large contribution to the clustering signal from 'local' sources: $\sim 60\%$ of the signal at $30'$ is expected to come from sources with $z < 0.1$ and this fraction increases as one goes to larger angles. A scenario where the very nearby population is made up of a mix of spirals and ellipticals (starbursting galaxies and AGN) and the slightly more distant population begins to be dominated by AGN is consistent with a clustering amplitude fairly close to that of 'normal' galaxies plus a slope more similar to that observed for elliptical galaxies ($\gamma \sim 2.1$ for ellipticals).

Figure 2(b) shows the effect of varying cosmological parameters on the predicted CF's but, given the above comments, it is somewhat misleading. It appears that an $\Omega_0 = 1$ model with a high Hubble constant fits the data best, but this assumes that all the sources have similar clustering strengths. On large angular scales (larger than $\sim 30'$), however, the CF is probing nearby structures and seems to be indicating a bias, b, for these sources of a little more than 1 (where $\xi_{radio} = b^2 \xi_{mass}$). On the smaller scales where one expects to be more sensitive to

higher-z clustering, a larger bias is required if models with popular values of H_0 are to fit. This is consistent with the difference in clustering strengths measured by PN for local AGN ($10h^{-1}$Mpc) and that measured for optically observed galaxies.

The angular CF of radio sources associated with $E > 19$ galaxy matches is significantly higher than what one would expect for a normal sample of $E > 19$ APM galaxies. This can be explained if the APM galaxies with radio counterparts are, on average, closer than all APM galaxies with $E > 19$. Ultimately, one would like to investigate clustering at high-z, but this is difficult given that the angular CF measured here appears rather sensitive to the clustering of a nearby population of sources which probably does not have the same clustering strength as the population at higher-z. In a preliminary attempt to isolate the clustering of the AGN-dominated sample at higher-z, we determined the CF for all sources *without* galaxy counterparts. The r_o's inferred from this measurement (with a linear evolution assumption) ranged from $10h^{-1}$Mpc to $15h^{-1}$Mpc depending on the redshift model. If the redshift distribution were better determined in the moderate-z range (beyond what one expects for APM galaxies, but not so far that the projected clustering becomes negligible), we could compare the clustering in this range with PN's measurement for local AGN to investigate the evolution of clustering in a more homogenous population.

5. Weak Lensing

Since it is not clear how light traces mass, it is desirable to find methods of probing mass fluctuations directly. In optical images, the weak gravitational lensing (coherent distortion) of background sources by foreground matter distributions has been used to probe cluster-scale masses and the use of similar techniques to probe larger mass scales has been discussed (see Kaiser 1996 and references therein). Here, we outline a preliminary search for a weak lensing signal in FIRST. A detailed discussion will be given in Refregier et al. (1997).

We start by defining the ellipticities of the sources. If a and b are the major and minor axes of a source and α is its position angle measured relative to some arbitrary set of axes defined on the sky, then stretching along these axes can be measured by $\epsilon_+ = \epsilon \cos(2\alpha)$ and stretching at 45° to these axes is measured by $\epsilon_\times = \epsilon \cos(2\alpha)$ [where $\epsilon = (a^2 - b^2)/(a^2 + b^2)$]. It is helpful to define ellipticity correlation functions which are independent of the coordinate system. To do so, we define ϵ_+^r and $\epsilon_\times^r$ measured with respect to axes which are parallel and perpendicular to the line connecting 2 points which are being correlated. If ϕ is the angle between the sky axes and the axes defined by the two points then one gets $\epsilon_+^r = \epsilon_+ \cos 2\phi + \epsilon_\times \sin 2\phi$ and $\epsilon_\times^r = -\epsilon_+ \sin 2\phi + \epsilon_\times \cos 2\phi$.

One can then construct three ellipticity CF's, $C_1(\theta) \equiv \left\langle \epsilon_+^r(\vec{\theta}_0)\epsilon_+^r(\vec{\theta}_0 + \vec{\theta}) \right\rangle$, $C_2(\theta) \equiv \left\langle \epsilon_\times^r(\vec{\theta}_0)\epsilon_\times^r(\vec{\theta}_0 + \vec{\theta}) \right\rangle$ and $C_3(\theta) \equiv \left\langle \epsilon_+^r(\vec{\theta}_0)\epsilon_\times^r(\vec{\theta}_0 + \vec{\theta}) \right\rangle$. Under reflection along the line connecting 2 points, ϵ_+^r is invariant but $\epsilon_\times^r$ changes sign, so C_3 must always be zero.

These three CF's have been measured for sources in the FIRST catalog that

are not 'point' sources, i.e for all sources that have $a > 2''$. With this cut, there are about 60 sources deg^{-2}. The ellipticities used were those obtained *before* beam deconvolution, making the measured CF's only rough estimates of the true CF's. To obtain an estimate of the noise, the CF's were also measured for a randomized catalog in which sources are assigned random ellipticities. We found that the C_1's and C_2's measured in the catalog were well above the noise. The C_3's we measured were consistent with zero. While these results are encouraging, systematic effects are likely to contribute significantly to the signal and we are still studying these in detail.

We have also investigated what CDM models predict for C_1 and C_2. A COBE normalised model with $\Omega = 1$ and $h = 0.5$ predicts values which are above the noise. Normalising to popular values of σ_8, however, decreases the predicted signal. Further work is required before we will know if a weak lensing signal is detectable but if it were, it would provide a unique opportunity to probe mass fluctuations on scales that are very difficult to probe with optical surveys.

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